Imaging Spin Properties using Spatially Varying Magnetic Fields

Honors Research Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Bachelor of Science with Honors Research Distinction in Electrical and Computer Engineering at The Ohio State University

By

Dominic Labanowski

Department of Electrical and Computer Engineering

The Ohio State University

2012

Examination Committee:

Professor P. Chris Hammel, Advisor

Professor David Stroud

ABSTRACT

Electronic devices have advanced according to Moore's law for a number of years. The small sizes of modern electronics have led to new complications (due to short gate lengths, high transistor density, etc.) that will likely cause Moore's law to saturate in the next five to ten years. Spin-based electronic (spintronic) devices have the potential to improve device performance and decrease power consumption. These devices show promise in moving current computer technology forward in the areas of logic, storage, and communications. Achieving an understanding of spin-polarized transport in inhomogeneous magnetic environments is critical to the advancement of spin-based electronics. We are developing numerical and experimental tools to achieve this goal. We have developed a method for studying spatially varying spin lifetimes by applying strongly inhomogeneous magnetic fields to semiconductor samples. Simulations show interesting effects when spins diffuse in the spatially varying magnetic fields of a micromagnetic tip or a ferromagnetic injector (such as those used in spintronic devices). These results show promise for local imaging of spin properties. The results of this work have the potential to advance the development of spin-based electronics by providing a high resolution imaging tool that can be used to observe the behavior of spins in prototype devices.

ACKNOWLEDGMENTS

I would like to thank my advisor, Chris Hammel, for all of his support during the course of my project. Professor Hammel allowed me to begin my research early in my collegiate career by taking a risk on me as an untested freshman with no experience in the lab.

I thank Professor David Stroud for all of his help as we worked to develop our simulation. We would not have been able to complete our work without his expertise and input.

I would also like to thank Vidya Bhallamudi for all of his help throughout my undergraduate research experience. The work I have done on this thesis has been almost entirely in collaboration with Vidya, and without his guidance and constant assistance I am sure that my efforts would not have been successful.

Finally, I would like to thank the other graduate students in the Hammel group (past and present), including Rohan Adur, Andrew Berger, Jeremy Cardellino, Michael Herman, Michael Page, and Richelle Teeling for their experimental assistance and advice during my years with the group.

TABLE OF CONTENTS

Page

Abstract ………………………………………………………………………… iii

Acknowledgements ………………………………………………………………….. iv

List of Figures …………………………………………………………………….. vii

Chapters:

1. Introduction ………………………………………………………………….. 1
    - 1.1 Motivation ………………………………………………………………… 1
    - 1.2 Thesis organization ……………………………………………………...... 2
2. Background ………………………………………………………………….. 3
    - 2.1 Spin dynamics within semiconductors ………………………………… 4
    - 2.2 Optical and electrical spin injection / detection methods ……………. 5
        - 2.2.1 Optical spin injection / detection …………………….. 5
        - 2.2.2 Electrical spin injection / detection ………………….. 6
    - 2.3 Spin relaxation and precession ………………………………………. 7
3. Numerical analysis of spin behavior in spatially varying environments …….. 10
    - 3.1 Behavior of spins in spatially varying magnetic fields ………………. 13
        - 3.1.1 Spin response without diffusion ($D_s = 0$) …………….. 15
        - 3.1.2 Spin response with diffusion ($D_s \neq 0$) ………………… 16

3.2 Magnetic perturbation imaging 17
3.2.1 Image formation 17

4. Conclusions and future work 19

References 21

LIST OF FIGURES

Figure	Page
2.1 Spin precession around an external field ……………………………………….	8
2.2 Spin precession with continuous injection ……………………………….…	9
3.1 Simulation algorithm ………………………………………………………..	11
3.2 Spatial spin distribution (uniform field) ……………………………………….	12
3.3 Hanle curve comparison ……………………………………………………….	13
3.4 Simulation setup ……………………………………………………………….	14
3.5 Coordinate system representation ………………………………………………...	14
3.6 Spin response without diffusion …………………………………………………..	15
3.7 Spin response with diffusion …………………………………………………………	16
3.8 Imaging sample case ………………………………………………………………	18

CHAPTER 1

INTRODUCTION

1.1 Motivation

As current electronics reach barriers due to heat buildup and high power consumption, the field of spin electronics has emerged as a solution to these issues. Spin-based electronic devices, or spintronic devices, avoid the problems of conventional electronics by using changing electron spin, rather than a changing voltage, to transmit information. This allows devices to offer faster data processing while also offering lower power consumption. While promising, the field of spintronics faces several challenges it must overcome, such as efficient injection and control of spins, understanding spin behavior in complex fields, and implementation of spin devices in real-world environments. My work has focused on understanding spin behavior in the complex magnetic fields within spintronic devices.

Before spintronic principles can be successfully applied to consumer devices, however, the behavior of spins in complex environments must be understood. Spin lifetimes calculated from experimental measurements are much shorter than theoretical expectations, and the influence of impurities, inhomogeneities, and other departures from ideal structures are poorly understood. A technique that could spatially resolve local variations in spin density and spin lifetime would allow for a substantially better understanding of the impact of these impurities, moving the commercialization of spintronic devices closer to reality.

The research presented in this thesis aims to move current spintronics technology closer to the fabrication of functional devices by developing an imaging technique capable of high spatial resolution that can be used in conjunction with currently popular spin detection schemes (optical or electrical detection). Part of the difficulty in fabricating functional and feasible spintronic devices is that a spintronic device that has potential to be integrated into current computing devices must be electrical in nature (both injection and detection of spins). This makes imaging the function of devices difficult, as electrical detection schemes lack any spatial resolution. As such, most analysis of such devices depends on idealized theoretical models, which fail to account for defects and other realities of physical devices. Our method has the potential to add the capability of spatially-resolved imaging to electrical detection setups, allowing for a more detailed analysis of devices. This capability could lead to a better understanding of the reasons why spintronic devices fail to operate as theoretically predicted, eventually allowing these complications to be corrected and for commercial spintronic devices to become a reality.

1.2 Thesis organization

The work presented in this thesis is organized as follows:

- Chapter 2 provides background on the field of spintronics and the importance of spin imaging
- Chapter 3 describes the numerical analysis of spins in inhomogeneous environments
- Chapter 4 discusses future work and concludes this document

CHAPTER 2

BACKGROUND

The field of spintronics (or spin transport electronics) emerged as a result of discoveries made concerning the transport of spin-polarized electrons within solid-state devices. This early work included the discovery of giant magnetoresistance (the phenomenon utilized in almost all modern computer hard drives to recover stored data) in 1988 [1], and the proposition of a spin field effect transistor in 1990 [2]. Work in the field is based on the fact that electrons, in addition to charge, have spin, which can have a value of ± ½. This spin can be used to encode information, much like how we now use charge to encode data in conventional electronics (where a high voltage is commonly used to encode a 1, while a low voltage is used to encode a 0). Substantial progress has been made in the understanding of spin injection into semiconductors, manipulation of those spins, and detection of the final spin states [3]. In addition, recent work has brought researchers closer to the fabrication of the electrically controlled room temperature devices that will be necessary before spintronic elements can be successfully integrated into current technology [4].

Despite the recent advances in the field, much is still not understood about the behavior of spins in semiconductors. One area in particular that requires substantial further investigation are the mechanisms by which spin polarization is degraded within the complex magnetic environments present within spintronic devices. Experimentally observed spin lifetimes are often substantially shorter than those derived from theoretical calculations, and the influence of impurities and other inhomogeneities are poorly understood. An imaging technique that could obtain data about spin properties (ie. lifetime) at a high spatial resolution could provide substantial insight into the effect of such inhomogeneities, and allow for a much more detailed analysis and understanding of spin behavior in prototype spintronic devices [5].

2.1 Spin dynamics within semiconductors

In order to properly analyze potential imaging techniques, it was necessary to develop a simulation that was capable of modeling spin behavior in the presence of an arbitrary magnetic field. In order to achieve this goal, we turned to the spin diffusion equation, which can be seen in eq. 2.1 below.

$$\frac{\partial \boldsymbol{S}}{\partial t} = D_s \nabla^2 \mathbf{S} + \zeta(\mathbf{E} \cdot \nabla)\mathbf{S} + \gamma \mathbf{B} \times \mathbf{S} - \frac{\mathbf{S}}{\tau_s} + \mathbf{G} \tag{2.1}$$

Where **S** is the spin density, D_s is the spin diffusion constant, ζ is the mobility, **E** is the electric field, $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, **B** is the total vector magnetic field experienced by the spins, τ_s is the spin relaxation time, and **G** represents the spin generation term (ie. optical injection). **S** is a function of time *t* and spatial position **r** = (x,y) for the samples considered in our simulations. Each term within this equation serves to represent the impact that a specific phenomenon has on the change in the spin density with respect to time ($\frac{\partial S}{\partial t}$). The first term ($D_s \nabla^2 \mathbf{S}$) represents diffusion of spins from higher concentration to lower concentration. The second term ($\zeta(\mathbf{E} \cdot \nabla)\mathbf{S}$) represents the drift of spins in an electric field. The third term ($\gamma \mathbf{B} \times \mathbf{S}$) represents spin precession around an external applied magnetic field. The fourth term ($\frac{\mathbf{s}}{\tau_s}$) represents spin relaxation. The fifth and final term (**G**) represents the generation of spins. This equation can be solved analytically for simple cases, but requires numerical analysis for the cases we are interested in solving (namely spatially varying **B** and τ_s).

2.2 Optical and electrical spin injection / detection methods

The two most common injection / detection schemes used in current spintronic experiments are optical injection / detection and electrical injection / detection. Both methods have notable advantages and disadvantages, which are briefly summarized below.

2.2.1 Optical spin injection / detection

In optical spin injection / detection a circularly polarized laser is used to inject spins into a semiconductor. The handedness (left or right handed) of the laser light determines the polarity of the spins injected. After spins are injected into a sample (and manipulated), they can be detected by a number of different methods. The most common method is to use Faraday / Kerr rotation to detect the orientation of the spins by shining laser light on the relevant area and observing the change in polarization of the reflected light. Another method (the one used in our experiments) is to wait until the electrons that were spin-polarized by the injection laser relax from the conduction to the valence band, and then to analyze the polarization of the emitted photoluminescence.

Optical methods have the advantage of providing some spatial resolution (though limited by the diffraction limit of whatever light is used in detection), but are difficult to integrate with modern electronics that operate predominantly on electricity (rather than light) to transmit information. Perhaps more problematically, optical injection / detection methods can only be used in certain optically-active materials (notably not Silicon). This limits their usefulness in the development of spintronic devices, motivating the adoption of electrical injection / detection methods.

2.2.2 Electrical spin injection / detection

In electrical spin injection / detection, spin is injected into a semiconductor through an interface with a ferromagnet of known orientation. As current passes through the ferromagnet, spins which align with the direction of the magnetic field within the ferromagnet pass through it preferentially. This leads to a spin polarized current entering the semiconductor through the ferromagnetic ‘injector.’ Electrical spin detection works much the same way, in that current is allowed to flow out of the semiconductor through a ferromagnetic ‘detector’ of known magnetic orientation. The voltage measured at this interface can be used to determine the resistance across the semiconductor / detector interface. Detection of spin polarization at the detector is then accomplished by applying knowledge of the giant magnetoresistance effect – if the spins under the detector are aligned against the ferromagnet, a high resistance will be observed, while if the spins under the detector are aligned with the ferromagnet, a low resistance will be observed.

Electrical injection / detection has the advantage that, since it is based on electrical phenomena, rather than optical ones, it can be easily integrated with modern electronics. In addition, electrical injection / detection can also work with all materials; however it is challenging to find the right materials systems and to optimize them to achieve high injection efficiency. Due to the fact that two interfaces necessary for any electrical injection / detection setup, this inefficiency is compounded, leading to severe signal degradation on detection. A further complication with electrical injection / detection is the lack of spatial resolution. Once fabricated, a device utilizing this injection / detection method cannot alter its detection area – the spins observed will always be those immediately under the detector. This leads to difficulties in understanding the behavior of spins within the device, complicating the design of subsequent generations if a device is found to be operating outside of specifications.

2.3 Spin relaxation and precession

The spin information encoded on electrons can be manipulated (even to the point of destruction) through interaction between the electron's magnetic moment and an externally applied magnetic field. When an external field is applied, spins precess around the applied field as shown in Figure 2.1. This precession continues according to the $\gamma\mathbf{B} \times \mathbf{S}$ term from eq. 2.1, with a larger applied field leading to faster spin precession, until damping processes eventually cause the spin to align with the applied field.

In the case where the applied external field is transverse (at a 90 degree angle) to the direction of the spin in the semiconductor (and uniform across the sample), the spins will precess around the applied the field resulting in a behavior called a Hanle response. The Hanle response of a given sample is often visualized through the use of a Hanle curve, which is a plot of the spin component that remains along the original spin direction as a function of applied transverse magnetic field.

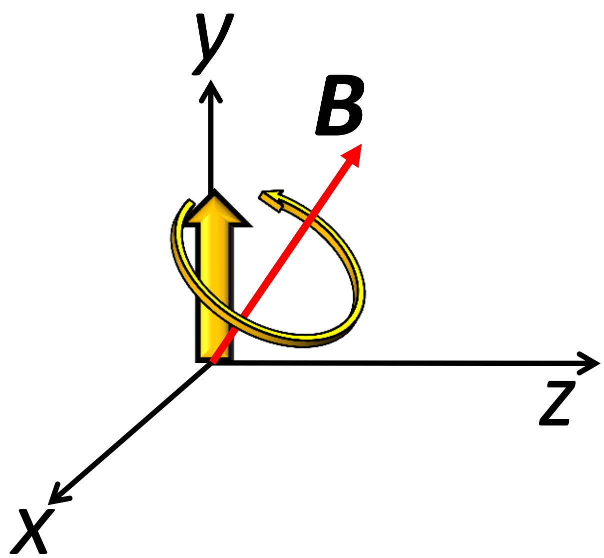

Figure 2.1: Precession of a spin around an applied external field **B**. The opening half-angle of the cone is the angle between the spin and the magnetic field.

In the case of continuous spin injection, and spin detection over the entirety of the sample, the Hanle response can be explained with the aid of Figure 2.2. Spins are injected and precess at a given rate based on the magnitude of the applied magnetic field (B_h). As a result, the spin component along the initial spin direction, S_z, is a function of both the magnitude of the applied magnetic field and the amount of time the injected spin has had to precess within the field. Due to continuous injection, at any given time there is a distribution of spins with different angles in the sample, as they have experienced the applied field for different periods of time. The larger the applied field, the greater the extent of this distribution.

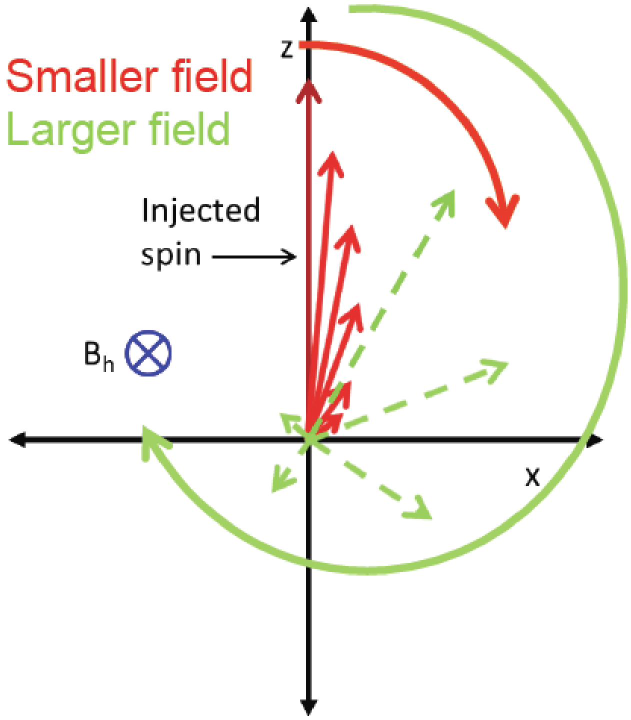

Figure 2.2: Precession of spins around a transverse applied magnetic field, B_h. The different arrows depict the precession of the spins over time, with the change in the size of the arrows being due to spin relaxation over time. This combination of procession and relaxation determines the net spin component of the spins along the original injection axis (z) and thus results in the Hanle response.

CHAPTER 3

NUMERICAL ANALYSIS OF SPIN BEHAVIOR IN SPATIALLY VARYING ENVIRONMENTS

This chapter will detail the bulk of the work done in completion of this thesis: using numerical analysis to understand the behavior of spins in semiconductors in the presence of spatially varying parameters (specifically magnetic fields and spin lifetime). For the cases we were interested in, namely spatially varying parameters with a non-zero diffusion term, numerical analysis had to be used as an analytical solution to the spin diffusion equation (eq. 2.1) does not exist for this case.

In order to better explain the final, complex cases for which the simulation was employed, I will begin by building off of a number of simpler cases. For the purposes of our simulations, we took $\mathbf{E}$ = 0 in the spin diffusion equation, as we did not anticipate performing any experiments where an electric field would be applied across the sample. This simplified eq. 2.1 into eq. 3.1 below:

$$\frac{\partial \boldsymbol{S}}{\partial t} = \mathbf{G} + D_s \nabla^2 \mathbf{S} + \gamma \mathbf{B} \times \mathbf{S} - \frac{\mathbf{S}}{\tau_s} \tag{3.1}$$

For all simulations done for this thesis, the spin injection term **G** in eq. 3.1 was assumed to take the form of Gaussian optical injection. As a result, **G** takes the form

$$\mathbf{G}(r) = G_0 \exp\left(-\frac{2r^3}{r_{pu}^2}\right)\hat{z} \tag{3.2}$$

where $G_0$is the maximum intensity of the Gaussian beam, r_{pu} is it's radius, and $\hat{z}$ is the injection direction of the spins.

While this equation is solvable analytically for simple **B** fields, it must be solved numerically for the complex field cases we were interested in analyzing. To accomplish this, an Euler approximation was used to solve for the steady state solution of the spin density, **S**. A diagram of the algorithm used can be found in Figure 3.1.

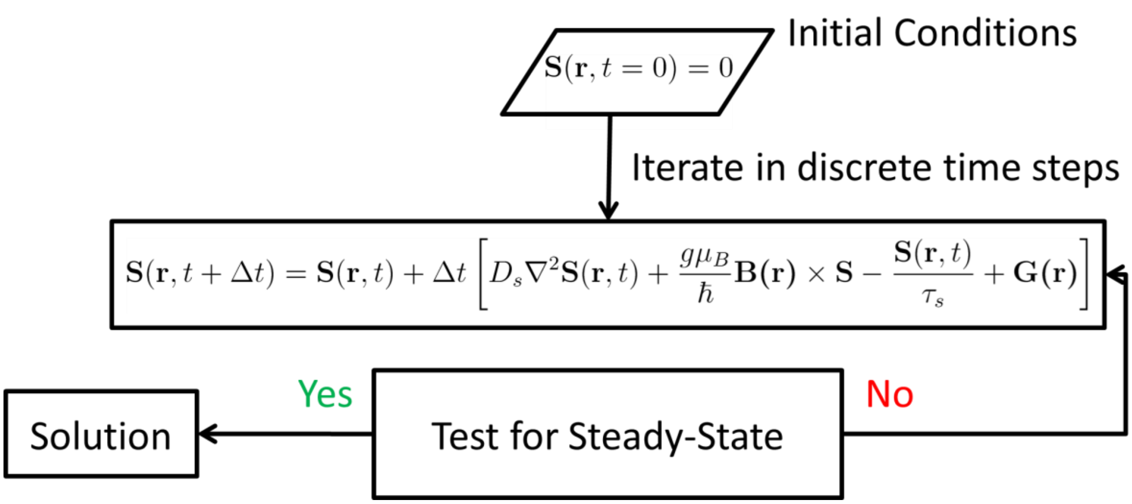

Figure 3.1: Algorithm used to numerically solve the spin diffusion equation based on Euler's method.

In solving eq. 3.1 numerically, the Laplacian must also be evaluated numerically by discretizing our 2D sample representation into a grid of points separated by a distance Δx in each direction. In this case,

$$\nabla^2 \mathbf{S}(\mathbf{r}, \mathrm{t}) \sim \frac{1}{(\Delta x)^2} \sum_{\xi} \left[\mathbf{S}\left(\mathbf{r} + \Delta \mathrm{x} \hat{\xi}, t\right) - \mathbf{S}(\mathbf{r}, t) \right] \tag{3.3}$$

Where $\hat{\xi}$ represents all unit vectors along the spatial grid (in this case $\pm\hat{x}$ and $\pm\hat{y}$).

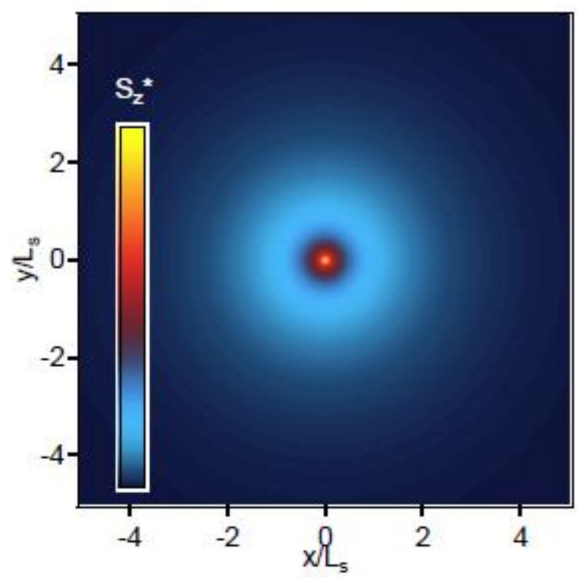

Figure 3.2: Sample spatial map of S_z (the spin component along the direction of original injection) for spins diffusing in a uniform magnetic field, assuming Gaussian injection with r_{pu} much less than the spin diffusion length.

In an effort to test whether the simulation was generating reasonable results, cases for which an analytical solution to the spin diffusion equation exists, and for which we have experimental data, were simulated. The three cases were then compared. In order to interpret the calculated results, however, they first had to be converted from spatial maps to plots of spin polarization versus applied transverse magnetic field (the Hanle curves discussed in 2.3). This was done by calculating the spin polarization at every point in the sample area and then summing those values to find the total polarization of the sample.

As can be seen in Figure 3.3, our simulations lined up well with both experimental data and the analytical solution to the spin diffusion equation for this case.

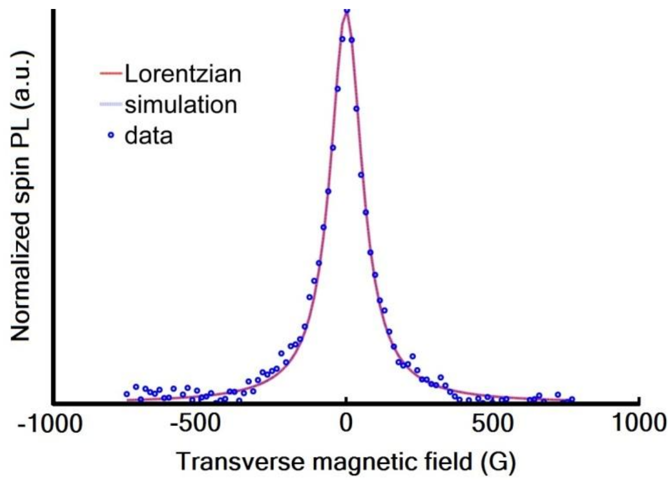

Figure 3.3: Comparison of the analytical solution to the spin diffusion equation (Lorentzian), simulation results (simulation) and experimental data (data). The Lorentzian and simulation lines are immediately on top of each other, and thus difficult to distinguish.

3.1 Behavior of spins in spatially varying magnetic fields

Once the simulation was tested for cases involving uniform magnetic fields, it was applied to the cases for which it was originally conceived: predicting the behavior of diffusing spins in the presence of a local magnetic dipole. A diagram of the system we are interested in simulating can be found in Figure 3.4, while the coordinate system used for these discussions can be found in Figure 3.5. This system was chosen for simulation as it closely mimicked experiments being carried out in the lab at the same time. The effects of the micromagnet on the spins within the semiconductor were not well understood, and simulating the setup was necessary to gain the understanding required to properly interpret the experimental results.

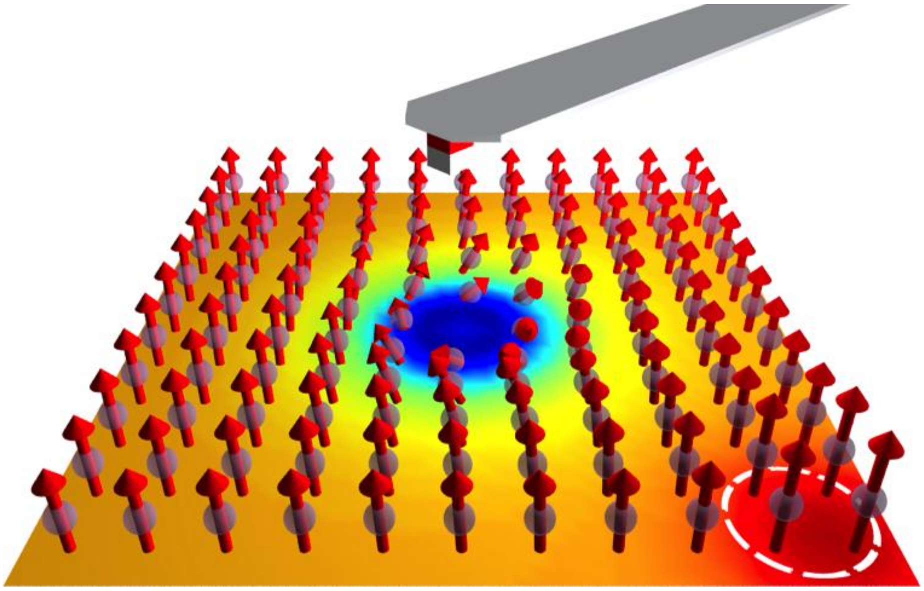

Figure 3.4: Schematic of the main geometry we are interested in simulating. Current simulations assume uniform spin injection, but are capable of simulating non-uniform spin properties (like the region of high spin lifetime indicated by the dashed white circle). The arrows depict the direction and magnitude of the spins, while the color map indicates their component along the injection direction (red > yellow > blue).

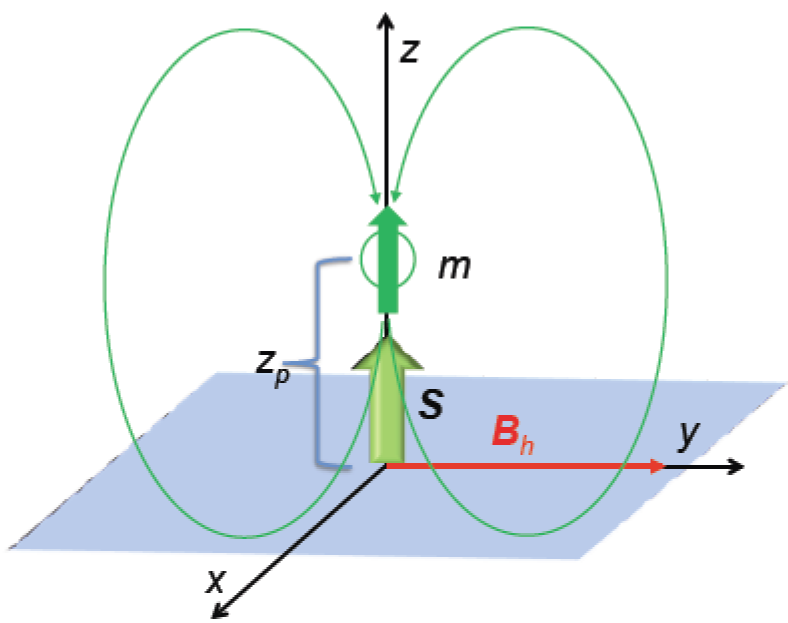

Figure 3.5: The 2D sample is assumed to be in the xy plane, spins (**S**) are injected along the z-axis, and the dipolar micromagnet is also oriented along the z-axis, and located at a height z_p above the sample plane. The Hanle field, $\mathbf{B}_h$, is assumed to be along the y-axis.

3.1.1 Spin response without diffusion (D_s = 0)

In the absence of diffusion, the same techniques applied previously to cases of uniform field can be applied to spins in the presence of a spatially varying field. This is due to the fact that since the spins are not moving in space, each only experiences one field value for all time. When a sample and magnetic dipole are oriented as shown in Figures 3.4 and 3.5, this leads the spin density shown in Figure 3.6.

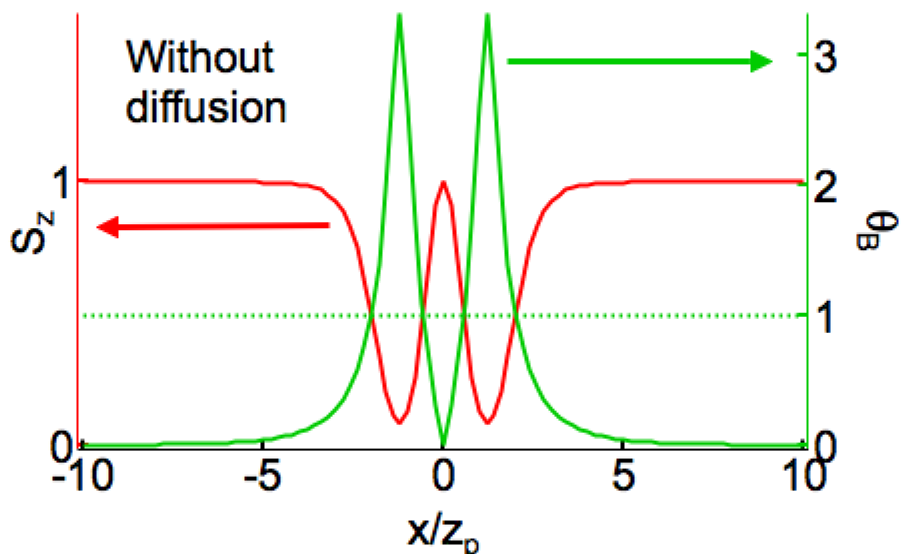

Figure 3.6: A line cut through y=0 of the sample geometry depicted in Figure 3.4. The spin component along the original direction of spin injection (S_z) is shown in red, and θ_B is shown in green. As can be seen, S_z immediately underneath the dipole field is unaffected, while S_z in close proximity to the center is greatly diminished.

In the above figure, θ_B is given by

$$\theta_B^2 = \frac{\gamma^2 \tau_s^2 B_\perp^2}{1 + \gamma^2 \tau_s^2 B_\parallel^2} \tag{3.4}$$

Where $B_\perp = \sqrt{(B_x)^2 + (B_y + B_h)^2}$ and $B_\parallel = B_z$.

Essentially, θ_B is the ratio between the field components perpendicular to the injected spin direction ($B_\perp$) and those parallel to the injected spin direction ($B_\parallel$). In areas where the dipole field at the surface of the sample is predominately in the perpendicular direction (large θ_B), the S_z component of the spin is suppressed, while in areas where the field is predominantly parallel (small θ_B) the S_z component of the spin remains undisturbed.

3.1.2 Spin response with diffusion ($D_s \neq 0$)

While an interesting case from a purely theoretical point of view, the diffusionless case presented in the previous section has little similarity to real devices. In order to more accurately model the behavior of spins within physical devices, it is necessary to take diffusion of spins into account. When the simulation is run for the same parameters as in the previous section, but with a non-zero diffusion constant. As long as the peaks in θ_B are sufficiently close, an interesting effect appears in that the central peak in the spin distribution collapses, leading to a distribution as depicted in Figure 3.7.

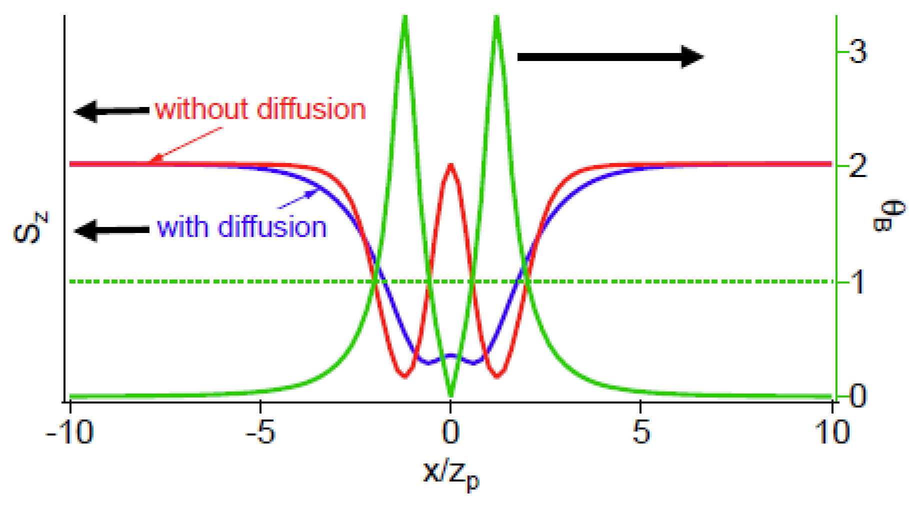

Figure 3.7: The same line cut depicted in Figure 3.6, but with the additional diffusion case depicted in blue.

The effect of diffusion on this system is to move spins located in the regions of high concentration (such as in the center and on the periphery) towards the region of low concentration (where θ_B is high). This has the effect of creating a 'hole' in the spin distribution directly underneath the magnetic dipole.

3.2 Magnetic perturbation imaging

The ability of a micromagnetic tip to form a localized 'hole' in the global spin density without significantly altering other portions of the sample presents an interesting opportunity. This ability could be used to encode local information about spin properties within a variation of the global spin polarization. As a result, this technique could be used to get spatially resolved information about variations in spin lifetime, and other key parameters, within complex spintronic devices. The fact that such imaging only requires one to examine changes in the global (not spatially resolved) signal means that this technique could be applied in both optical and electrical detection setups, making it the first spatially resolved imaging method that can be implemented in any materials system. The general setup of this method is the same as the schematic pictured in Figure 3.4. A micromagnetic tip is scanned about the sample, and global spin signal is observed as a function of tip position. Using the simulation results as a basis for reconstruction, the spin properties of the sample that are suppressed by the 'hole' at each tip position can then be reconstructed.

3.2.1 Image Formation

A simple case by which this imaging method can be understood is presented in Figure 3.8. Spins are injected uniformly along $\hat{z}$ into a sample that has a region of high spin lifetime in the bottom left corner, as depicted in 3.8(a). As the tip is scanned across the sample in an x-y grid pattern, the global spin density is recorded. This results in a plot like the one found in 3.8(b), which shows a variation in the globally observed spin density as the micromagnetic probe approaches the region of inhomogeneity caused by the region of high lifetime. In this region, the spin density is higher (as spins survive longer once injected) and thus the 'hole' burned by the tip removes more from the global population than it would in the bulk sample. This is reflected in the global spin density by a dip in the global spin signal while the micromagnetic tip is located in this region. Since the feature being used to remove spins does not have perfectly vertical sides (as seen in Figure 3.7), it area where the tip influence can be seen is significantly larger than the high lifetime area itself. Knowing the profile of the tip, this effect can be avoided by simply deconvolving the profile of the tip with the collected data.

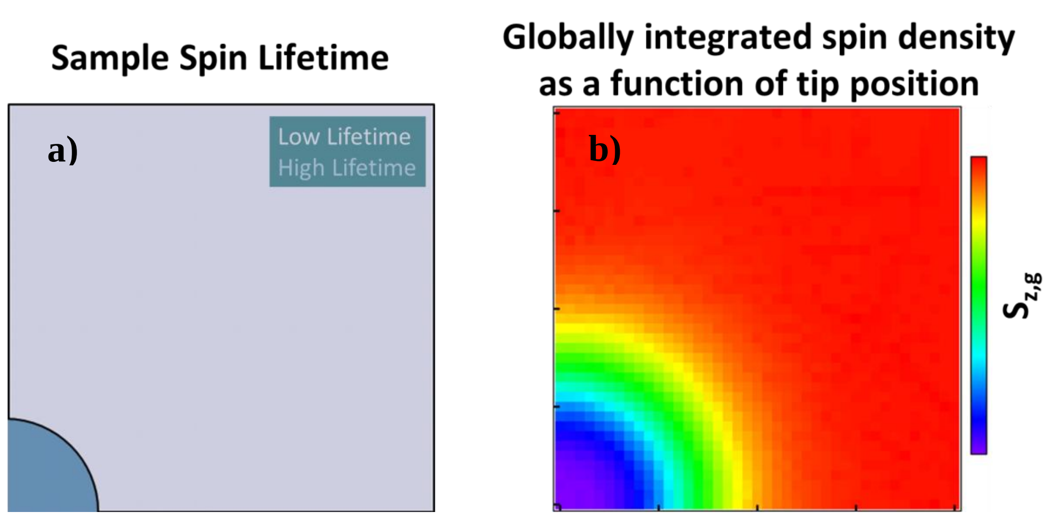

Figure 3.7: a) Demonstration sample with a region of high spin lifetime located in the bottom left corner. b) Global spin polarization as a function of tip position, revealing the region of high lifetime seen in (a)

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

The numerical analysis tool presented within this thesis has the capability of being applied to a number of different systems not discussed in this work. This tool has the capability of analyzing spin behavior in a wide variety of inhomogeneous systems, and can handle spatial and even temporal variations in ways that we have not yet tried. I believe this simulation, as well as the insight we have already gained with it in working on these experiments, may prove extremely valuable in guiding future experimental work and in understanding the performance of spintronic devices.

While this numerical analysis tool has thus far been extremely helpful in understanding our results, it is not without its flaws. One major area in which the simulation software could be improved is by upgrading our current Euler's formula-based algorithm to something more robust, such as the Runge-Kutta method. Current simulations tend to diverge and break down in the presence of strong field gradients, an issue that could be successfully avoided by upgrading the iterative algorithm. Also, there is room to add new functionality to the numerical analysis program, such as the ability to simulate spin behavior in three dimensions (important for better force estimations or for thick samples) or the ability to incorporate drift effects due to electric fields (like those present in exciting new materials like graphene).

In addition to this numerical tool, this thesis also presents a new technique for imaging spin properties in spatially inhomogeneous samples. This technique can be applied to a variety of materials systems by acting in conjunction with already proven detection techniques such as optical and electrical injection. These techniques are used to obtain a global spin signal, which is then modulated by moving a cantilever with a micromagnetic tip over the sample. This tip allows us to encode local information into the global signal. In order to analyze the collected data, it is useful to use our numerical analysis tool to better understand the effect the tip has on each particular sample, thus allowing for the high resolution imaging of spin properties in a sample regardless of the materials system utilized.

The proposed imaging method has a wide variety of potential future applications, not the least of which is analysis of fabricated spintronic devices. Such analysis would make it much easier to identify defects within the current generation of devices, allowing for corrections to be made more quickly and more effectively than without the use of this imaging method. Before this is possible, however, it will be necessary to experimentally verify the feasibility of this approach in a real system. Such experimental work is already underway within the lab, and if results are positive then it will open the door for a wide variety of applications for this imaging technique in the analysis of sample inhomogeneities within spin devices.

REFERENCES

[1] G. Binasch, P. Grünberg, F. Saurenback, and W. Zinn, *Phys. Rev. B* 39, 7 (1989)

[2] S. Datta and S. Das, *Appl. Phys. Lett.* 56, 665 (1990)

[3] X. Lou, C. Adelmann, S. A. Crooker, E. S. Garlid, J. Zhang, K. S. M. Reddy, S. D. Flexner, C. J. Palmstrom, and P. A. Crowell, *Nature Phys.* 3, 197 (2007)

[4] I. Appelbaum, B. Huang, and D. J. Monsma, *Nature* 447, 295 (2007)

[5] V. P Bhallamudi, A. J. Berger, D. E. Labanowski, D. Stroud, and P. C. Hammel, *J. Appl. Phys.* 111, 013902 (2012)